The 5th CCMC Workshop
Annapolis, MD, April 11 – 15, 2016

Multi-Scale Fluid-Kinetic Simulation Suite:
New Horizons Flyby Modeling Challenge
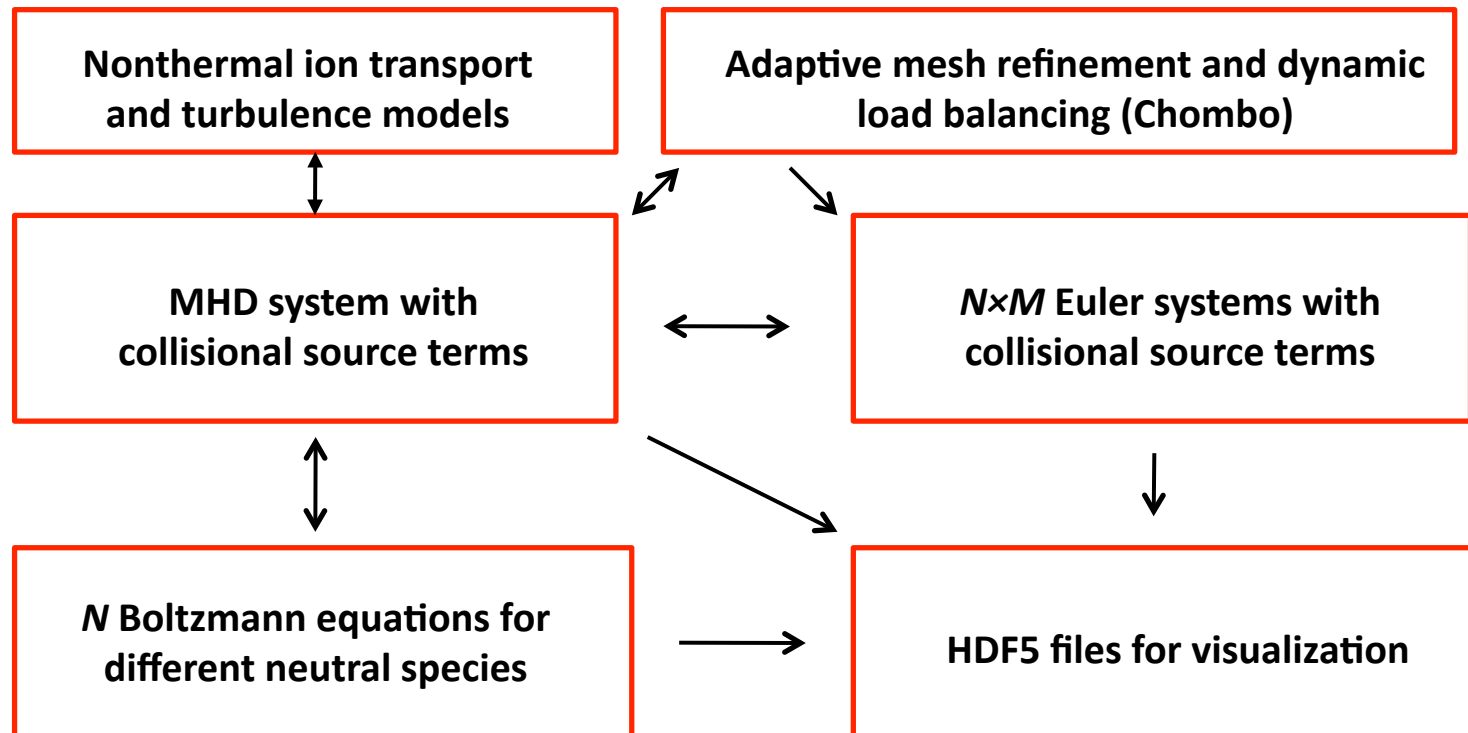
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Outline

- MS-FLUKSS capabilities
- Solar wind simulations based on OMNI data: The importance of turbulence
- Simulations with using boundary conditions from the Linker et al. model and comparison with MAS
- Modeling CME propagation with adaptive mesh refinement
- New Horizons simulations
- IPS data and solar wind modeling

MS-FLUKSS Capabilities

| Nonthermal ion transport and turbulence models | Adaptive mesh refinement and dynamic load balancing (Chombo) |

MHD system with collisional source terms

$N \times M$ Euler systems with collisional source terms

N Boltzmann equations for different neutral species

HDF5 files for visualization

The code is ported to major national supercomputers and demonstrated scalability to 160,000 computing cores. GPU implementation of the kinetic modules is under development.
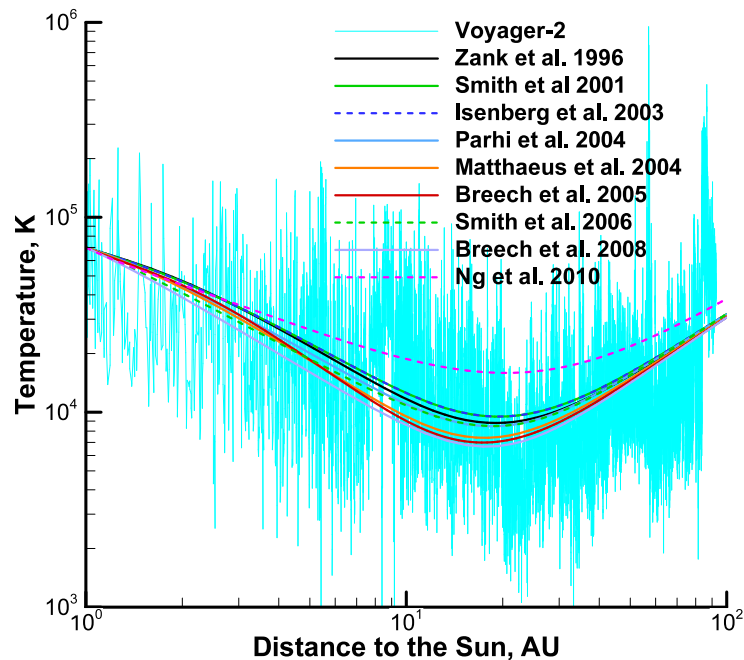
Solar wind with turbulence and pickup ions

Unsteady SW Based on the OMNI data
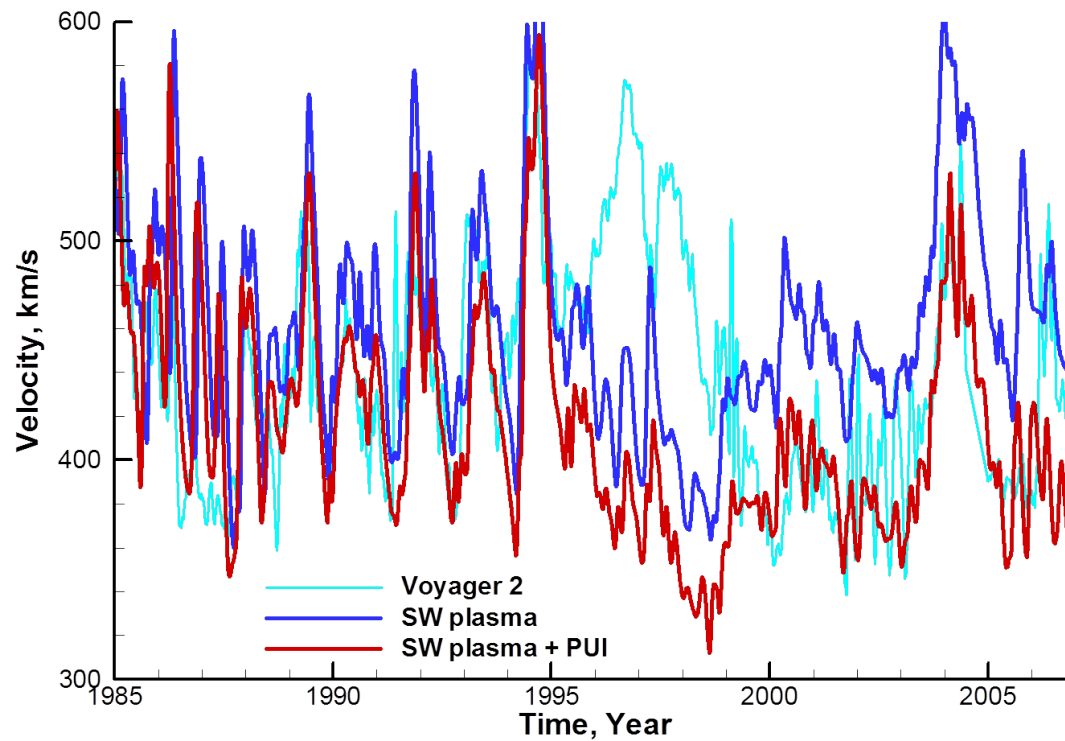
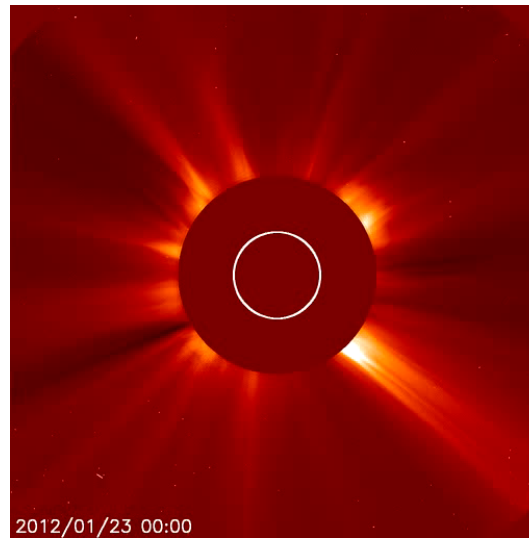**Measured and calculated SW velocity distributions along the Voyager 2 trajectory (the turbulence model from Breech et al., (2008).**
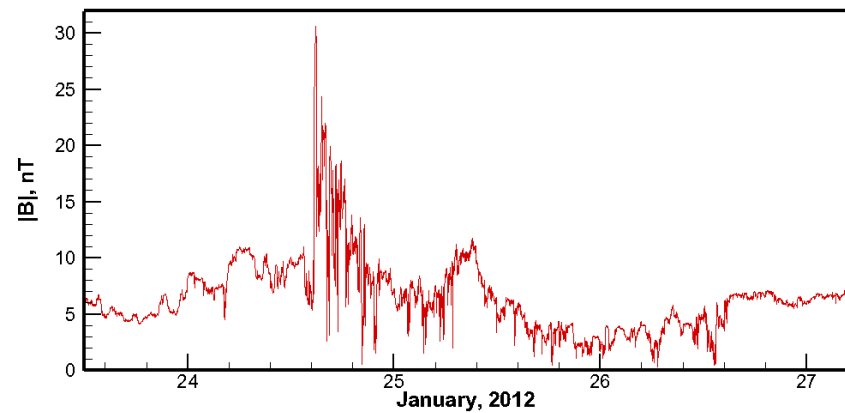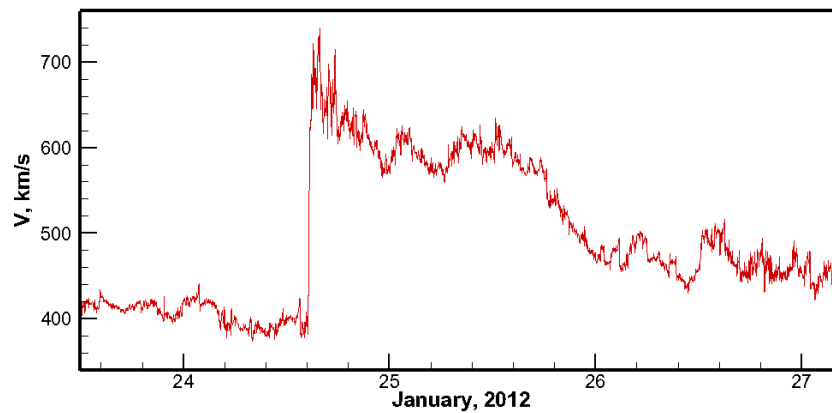
Our 3D turbulent solar wind model includes the Reynolds averaged MHD equations for plasma (SW protons + PUIs), the Euler equations for inter-stellar neutrals, two equations for PUIs, and turbulence model equations. We use the assumption that PUIs co-move with the SW velocity (*Isenberg*, 1986). We compare a number of turbulence models implemented in MS-FLUKSS.

Numerical simulation in the spherically symmetric SW from 1 to 80 AU with a plane HCS (Heliospheric current sheet) was performed with MS-FLUKSS.

Legend:
- Voyager-2
- Zank et al. 1996
- Smith et al 2001
- Isenberg et al. 2003
- Parhi et al. 2004
- Matthaeus et al. 2004
- Breech et al. 2005
- Smith et al. 2006
- Breech et al. 2008
- Ng et al. 2010

X-axis: Distance to the Sun, AU
Y-axis: Temperature, K

Kryukov et al. (2012)

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Coronal Mass Ejection on Jan 23, 2012

SOHO view of the CME

WIND observations of the SW at Earth orbit

Magnetic field lines
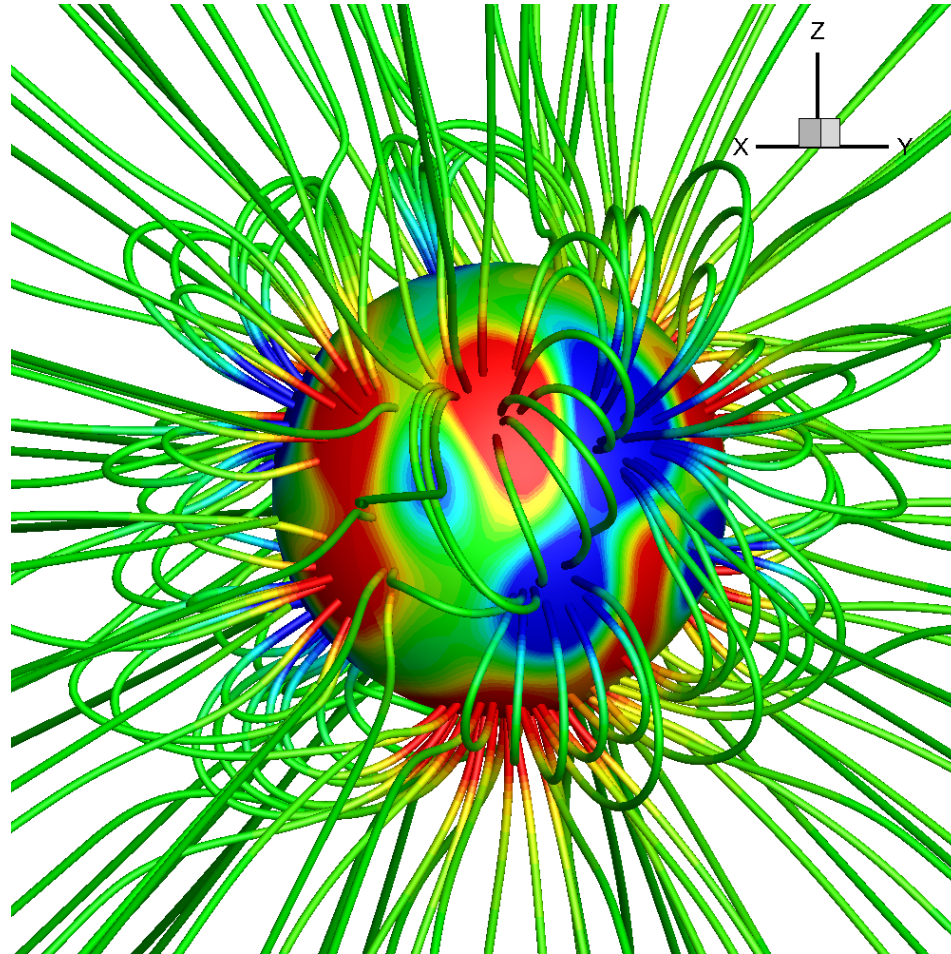
Magnetic field lines in January 2012

Coronal Mass Ejection Initialization

The CME is modeled by introducing a blob in the background flow at 1.5 Rs in the direction N6W27 relative to the Earth location. The blob radius is $a_{cme} = 0.33Rs$.

Parameters inside the plasma blob are taken from the Chané et al. (2005, 2006, 2008) model (implementation of Shen et al. 2011):
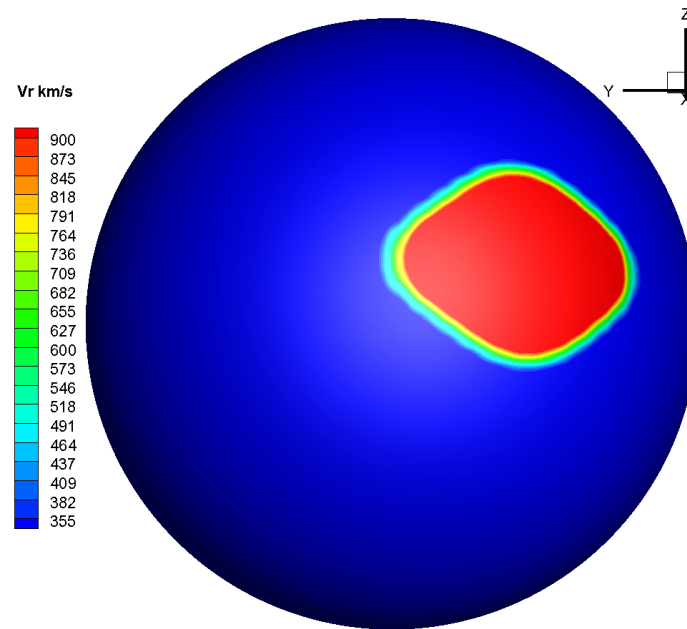
**Blob structure at 10 Rs as
visible from Earth**

Coronal Mass Ejection Simulation

CME simulation is done in two steps

1. Perform simulation in region 1Rs and 11 Rs and collect data at 10 Rs

2. Calculate CME propagation from 10 Rs to 1AU using Multi-Scale Fluid-Kinetic Simulation Suite (MS-FLUKSS) and adaptive mesh refinement technique (scales to 160,000 cores)

    Numerical method:
    Finite volume approach (Godunov type method)
    Explicit MUSCL-second order Hancock scheme
    8-wave Riemann solver

    Base grid is 256^3
    One level of refinement with the refinement ratio 4
    Effective resolution is 1024^3

Simulation results

Ecliptic plane

Slice through the CME center
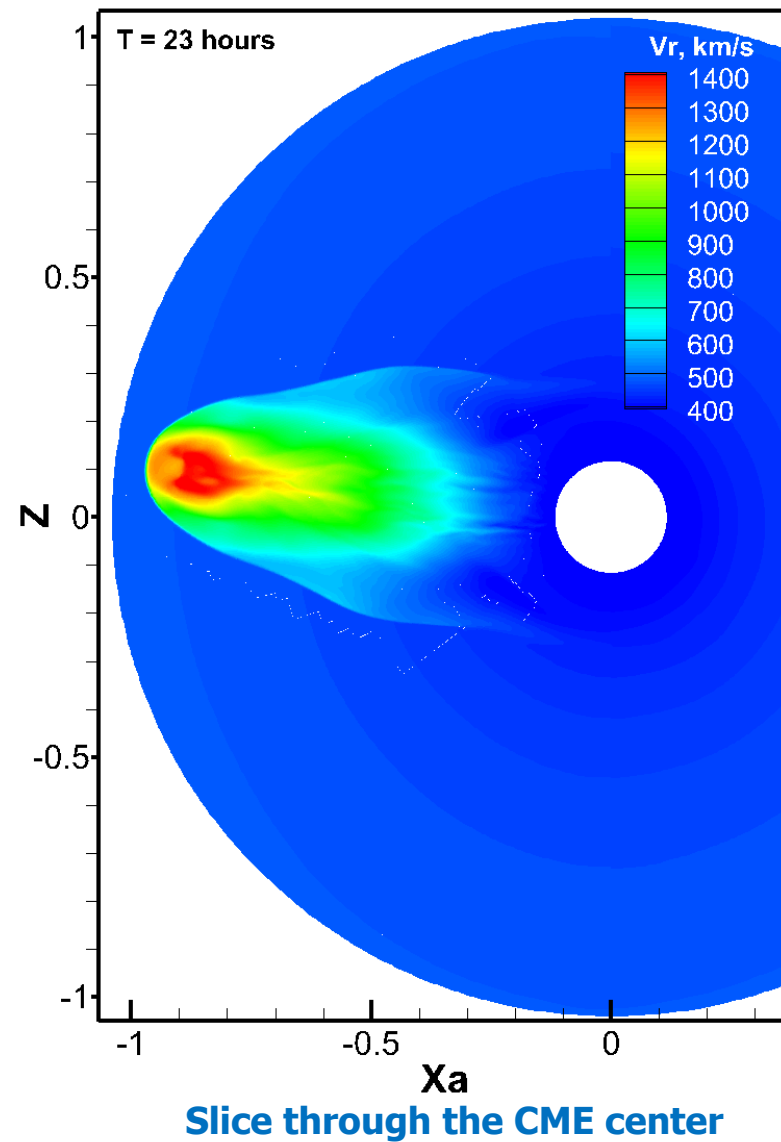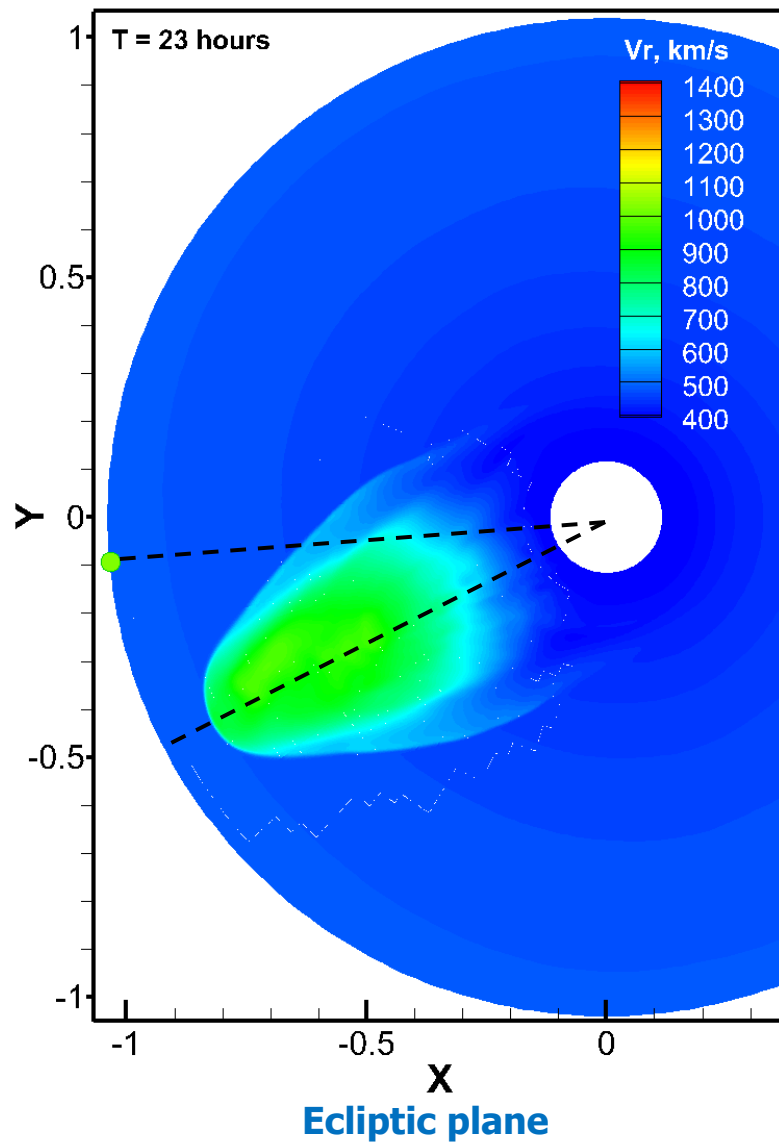
Simulation results, cntd.
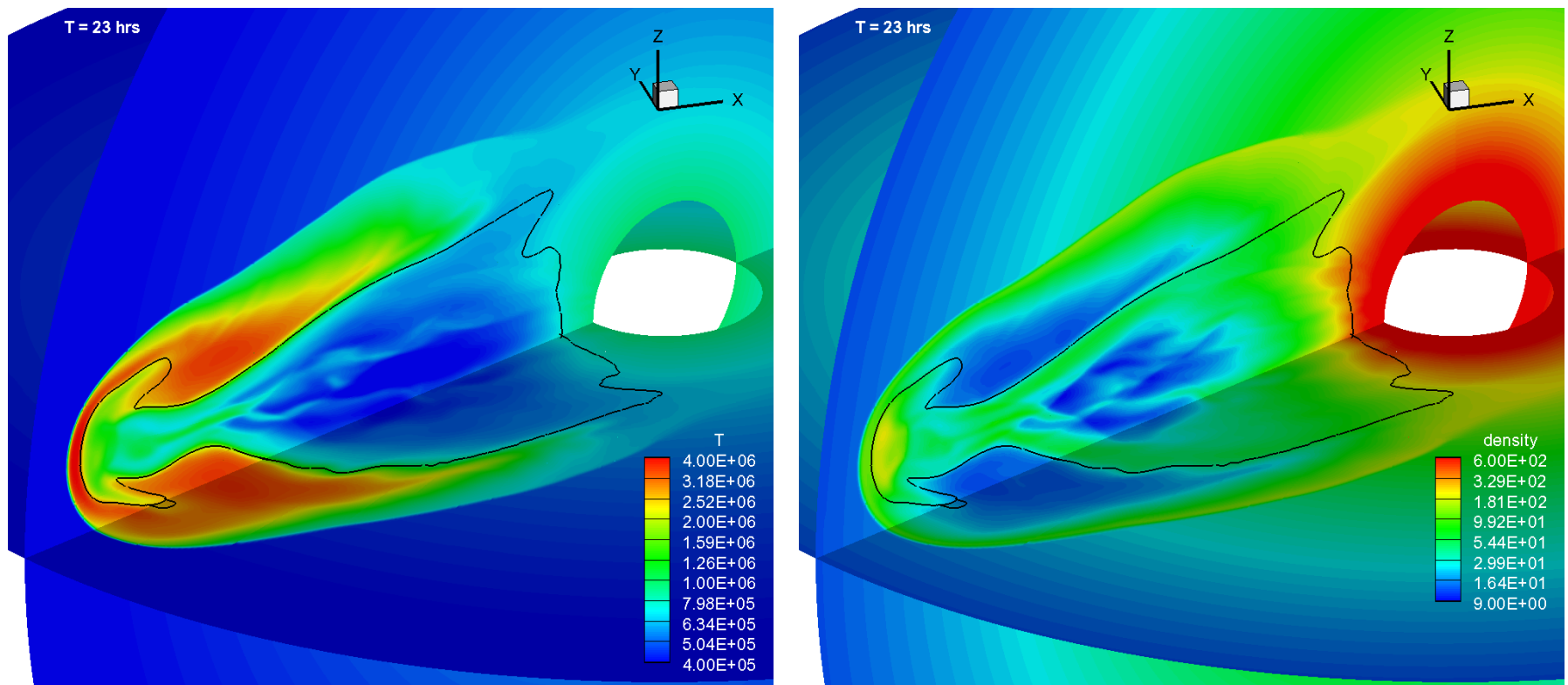
Temperature and density distribution at T = 23 hours after the CME launch

Simulation result, cntd

Ecliptic plane

Slice: Z-axis, Earth location

Simulation result, cntd

Ecliptic plane

Slice: Z-axis, Earth location
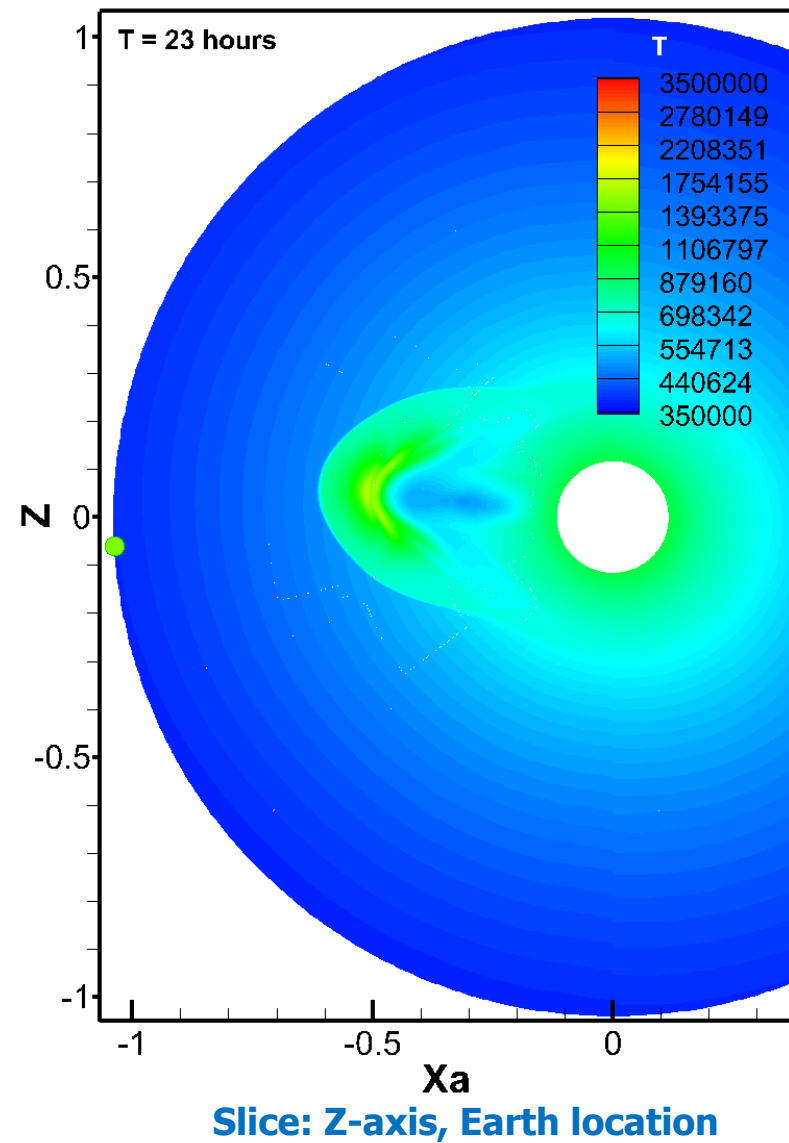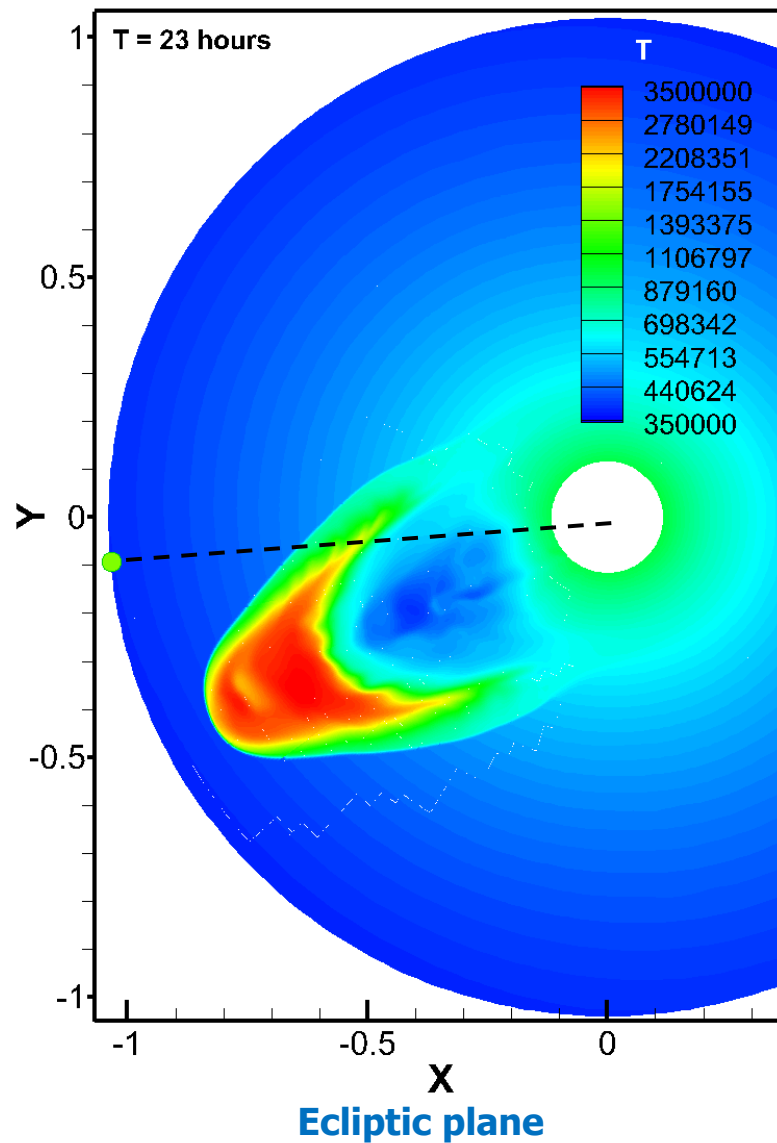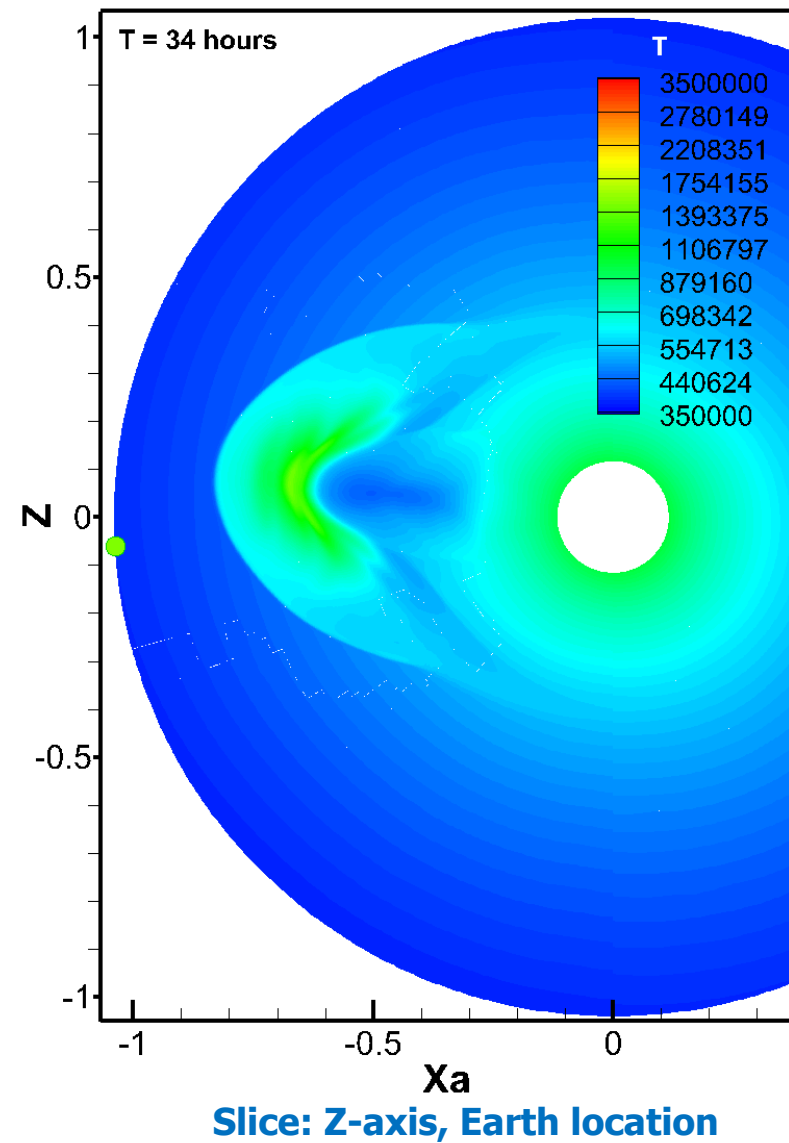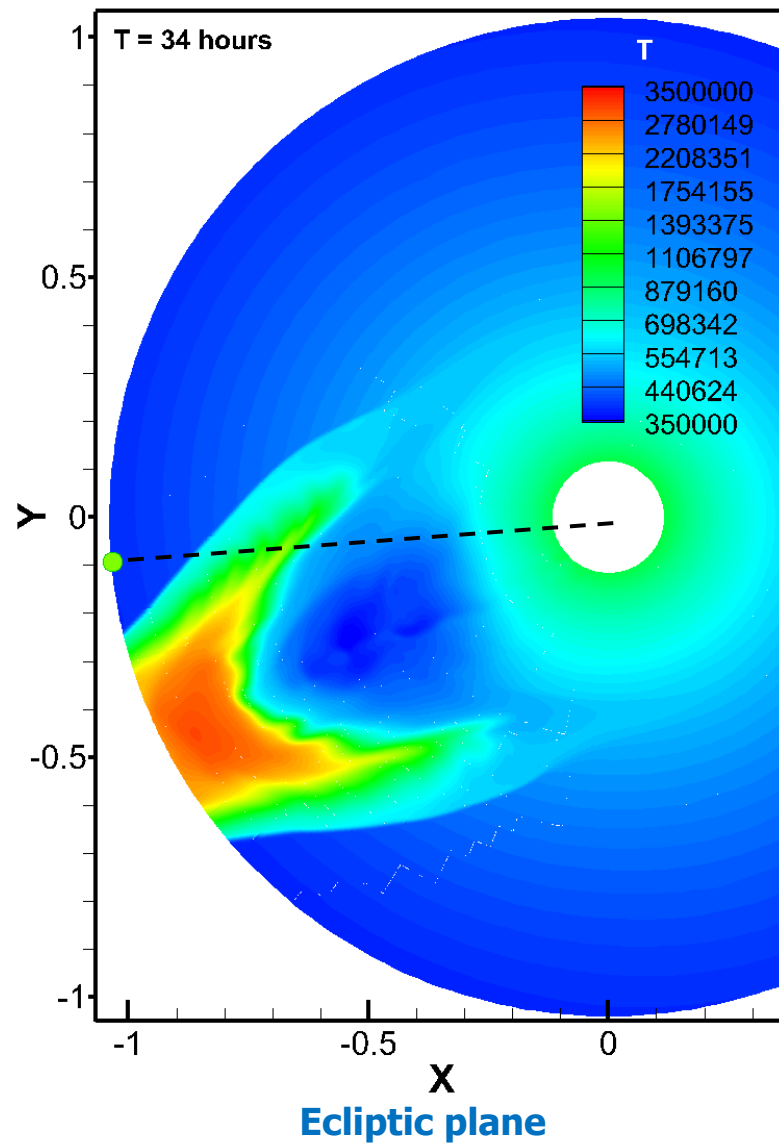
CME November 4,1997
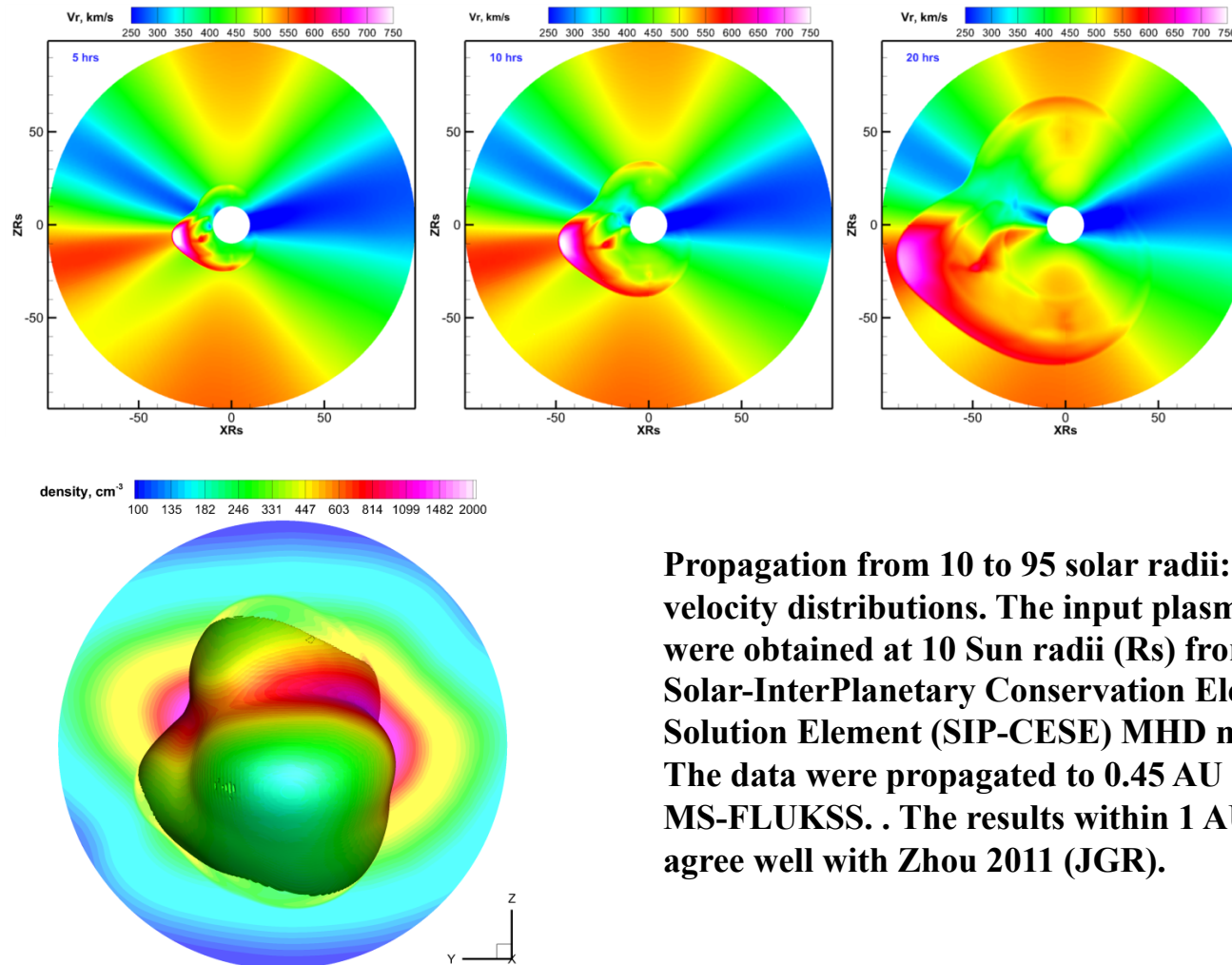
Propagation from 10 to 95 solar radii: radial velocity distributions. The input plasma data were obtained at 10 Sun radii (Rs) from the Solar-InterPlanetary Conservation Element/ Solution Element (SIP-CESE) MHD model. The data were propagated to 0.45 AU using MS-FLUKSS. . The results within 1 AU agree well with Zhou 2011 (JGR).
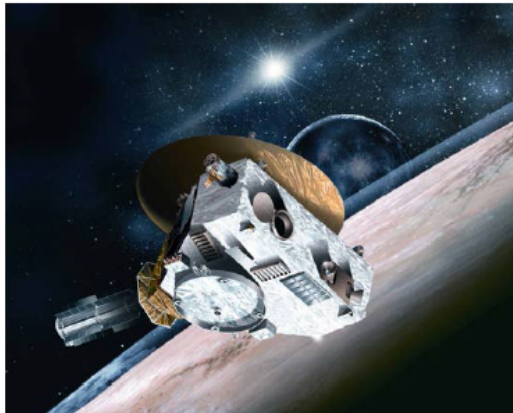
Comparison of MS-FLUKSS (bottom panels) and MAS (top panels)

VR

Plasma density
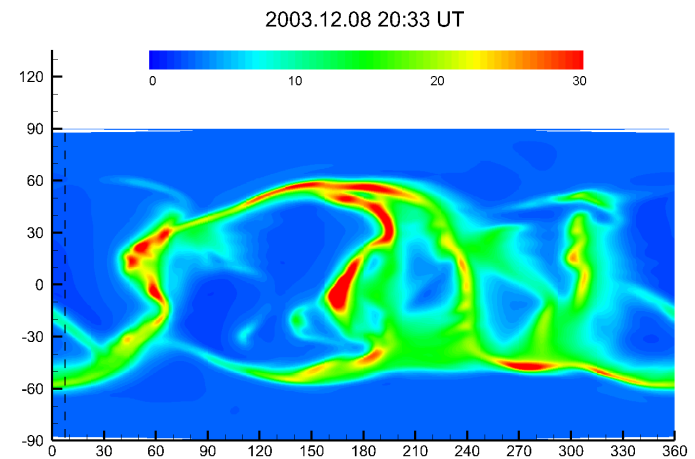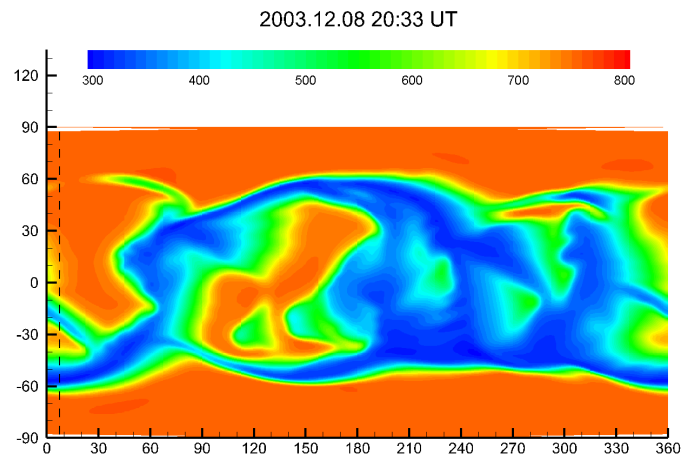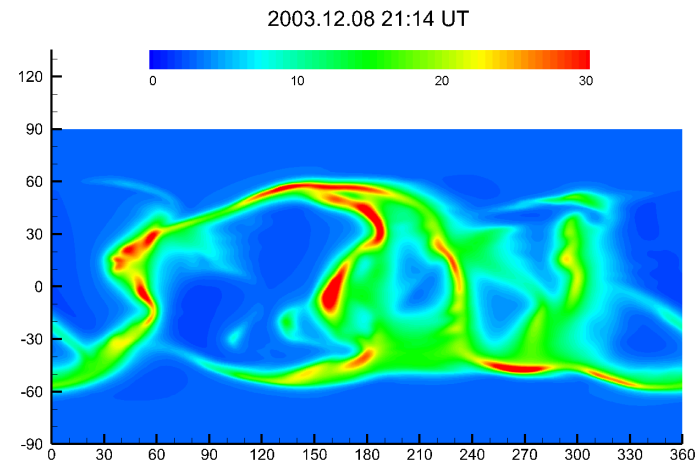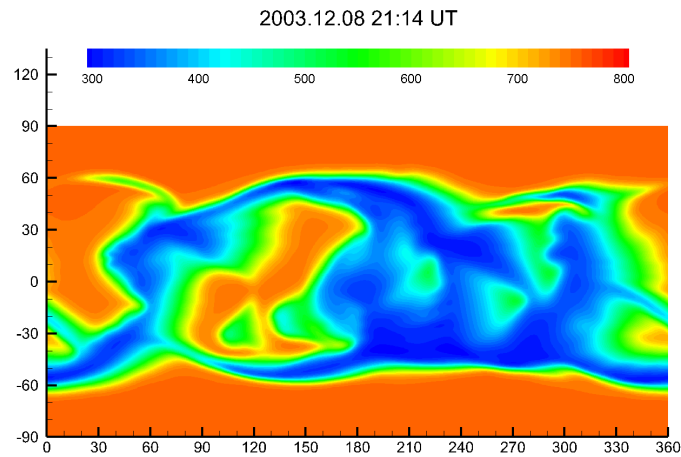
Comparison of MS-FLUKSS and MAS (contd.)

Bphi   BR
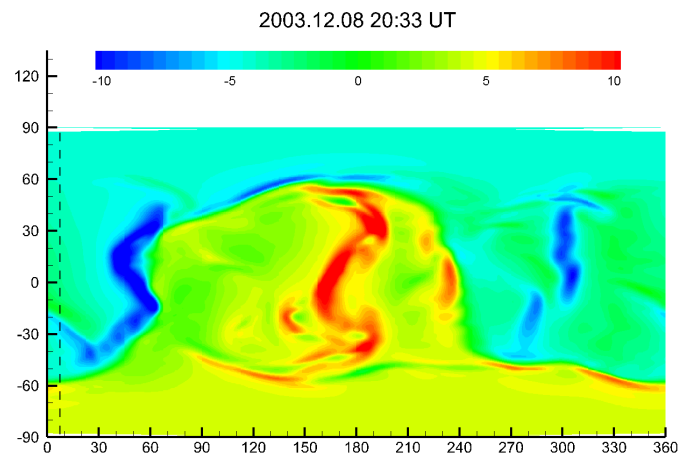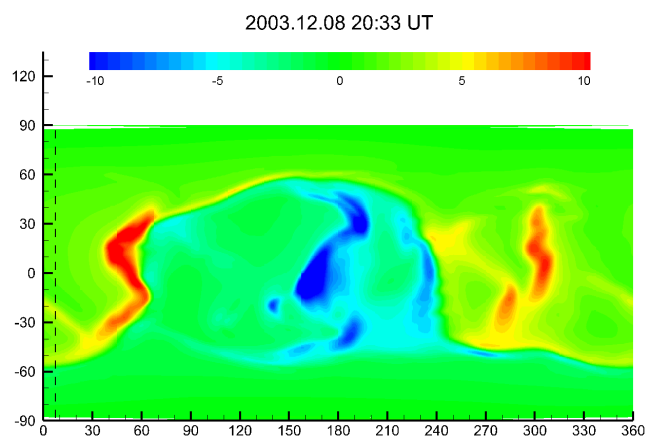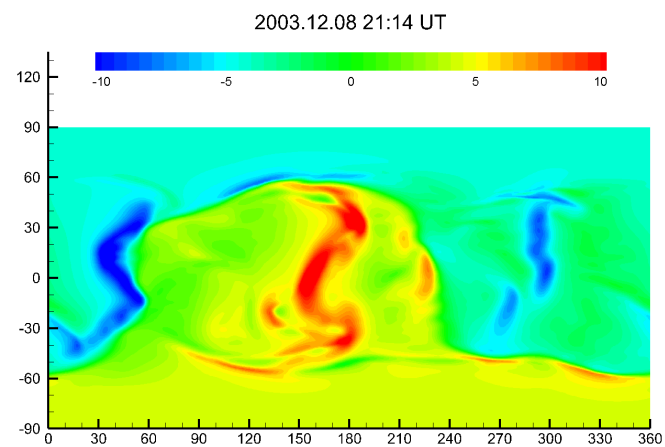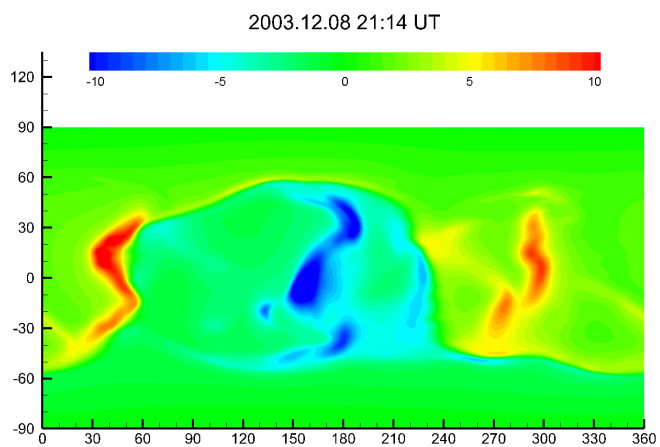
Charge exchange, PUIs, and Turbulence Matter

New Horizons Mission Support

Community-wide effort to provide solar wind modeling support for the New Horizons Flyby:
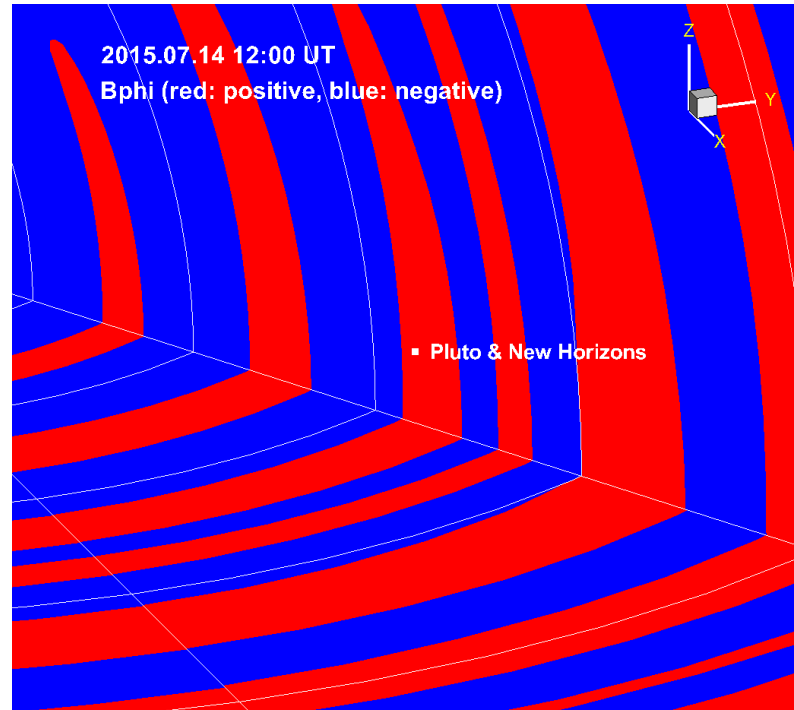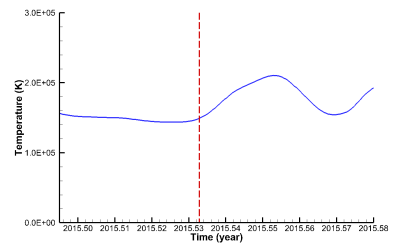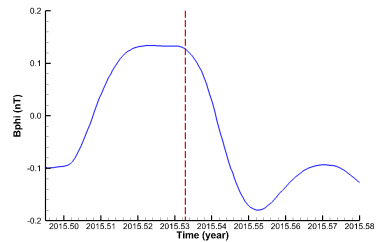
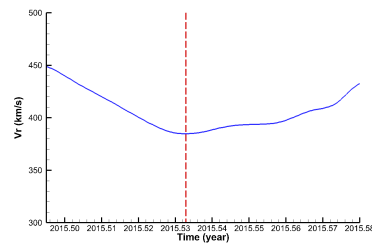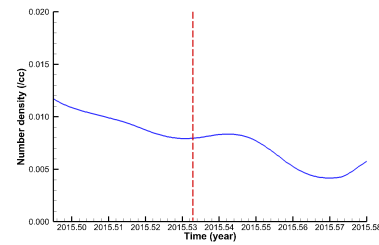"New Horizons Flyby Modeling Challenge"

Comparison with the New Horizons SWAP Data

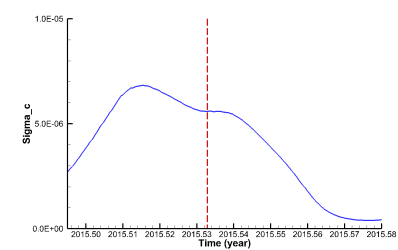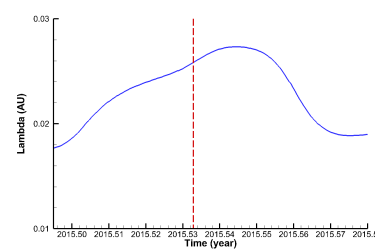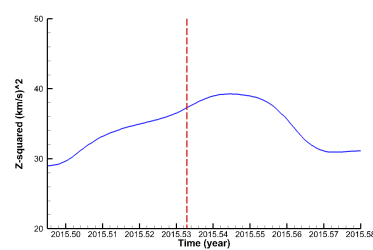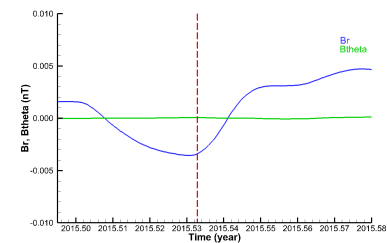**Simulations are based on OMNI data as boundary conditions.**
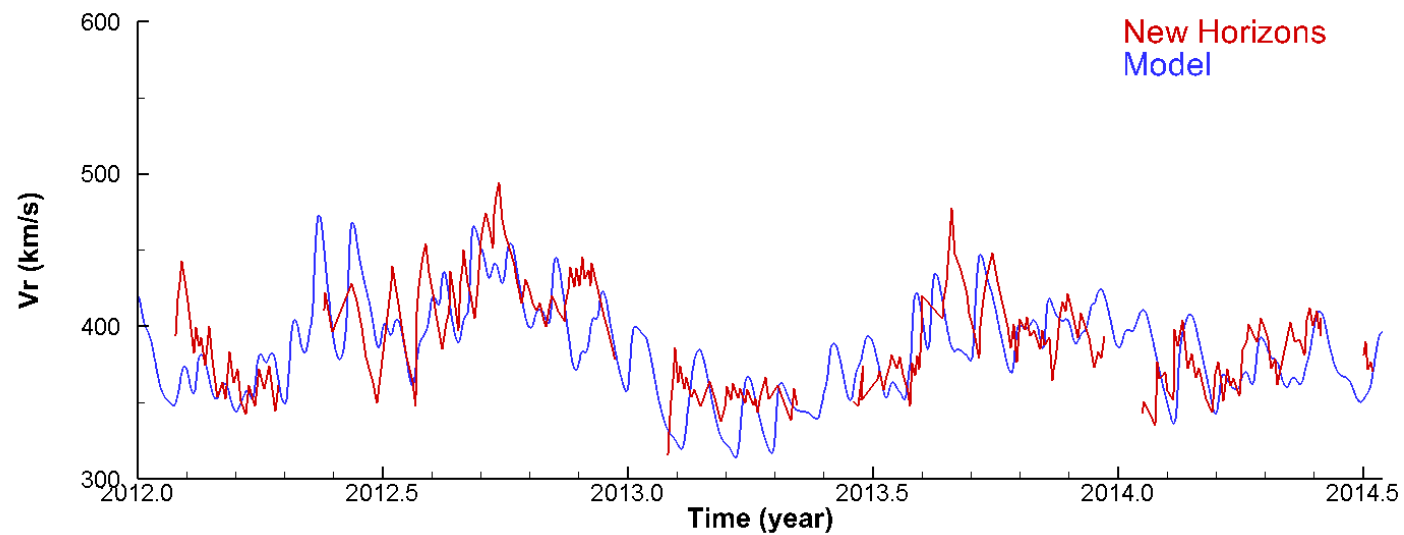
Adapted from Elliott et al. (2016)

New Horizons Flyby Modeling Challenge

2015.07.14 12:00 UT
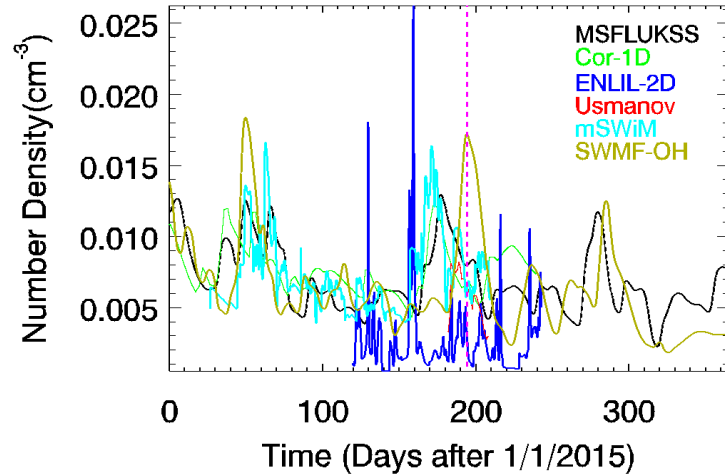Bphi (red: positive, blue: negative)

Pluto & New Horizons

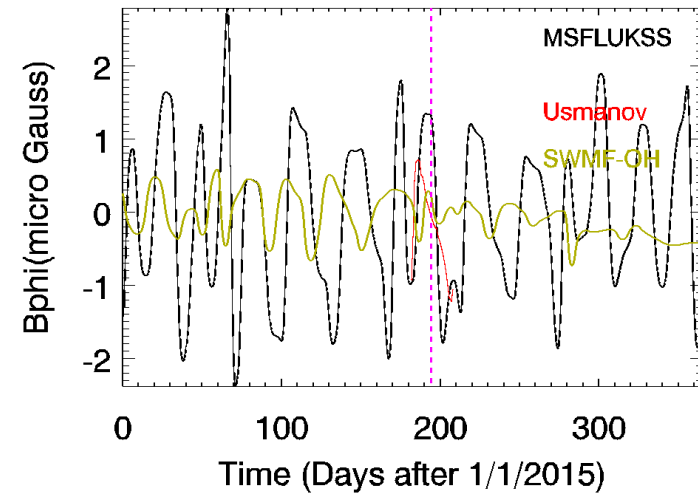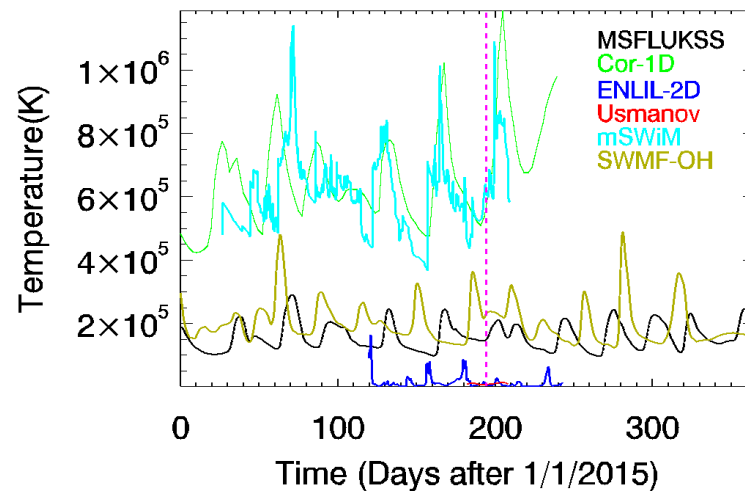http://ccmc.gsfc.nasa.gov/missionsupport/NewHorizons_MS-FLUKSS.php
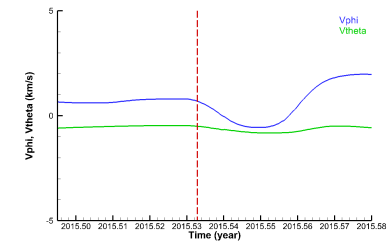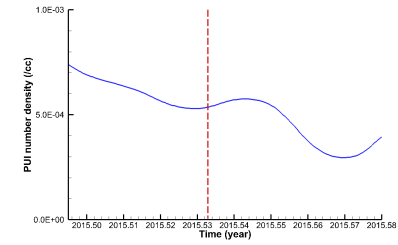
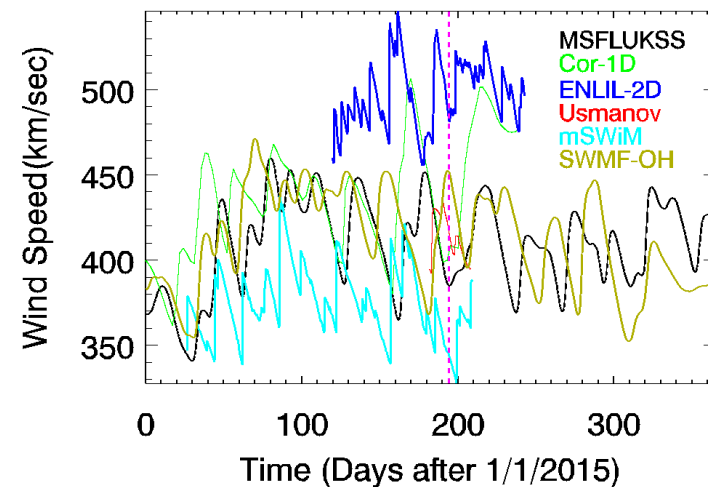# Model Comparison

New Horizons - Number Density

New Horizons - Bphi

New Horizons - Temperature

New Horizons - Wind Speed

Comparison with New Horizons at the Pluto Flyby

Plasma property	New Horizons SWAP	MS-FLUKSS
Solar wind speed (km s^{-1})	403	385
Proton density (cm^{-3})	0.025	0.008
Proton flux (km s^{-1} cm^{-3})	10	3.1
Proton temperature (K)	7700	13747
Proton thermal pressure (fPa)	2.5	1.4
Proton ram pressure (pPa)	6.0	1.8

Adapted from Bagenal et al. (2016)

MS-FLUKSS model driven by IPS observations of the solar wind and WSA
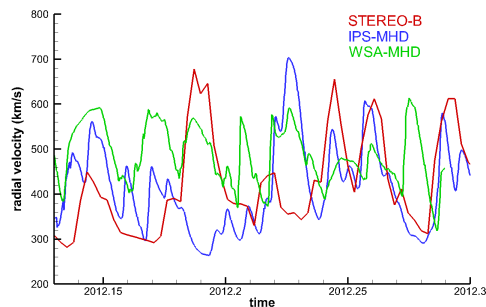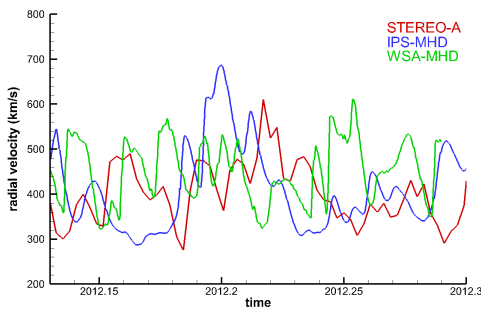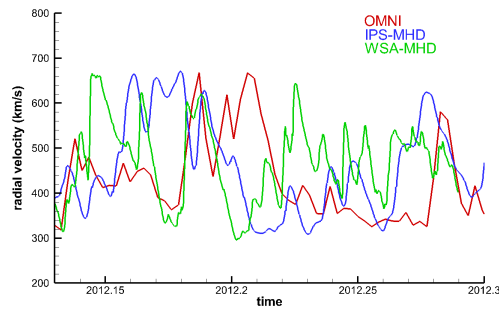
2012 DOY 046 – 106
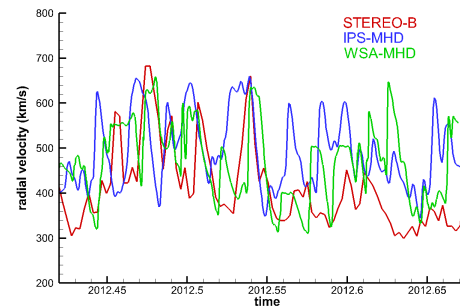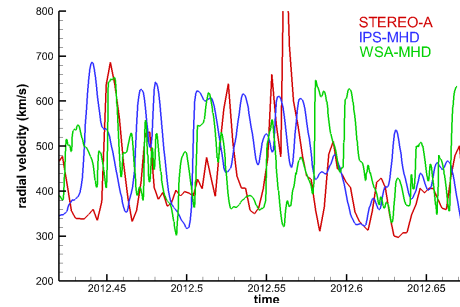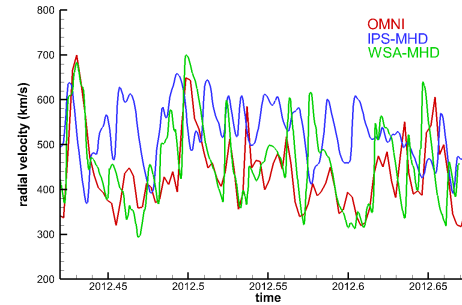
2012 DOY 153 – 244

Note: MHD simulation results using WSA model boundary conditions are shown for additional reference.

Conclusions

1. **MS-FLUKSS resolves shocks and tangential discontinuities with high precision making simulations results reliable once proper, data-driven or externally provided, boundary conditions are available.**
2. **Comparison with MAS provided us with a necessary validation.**
3. **A number of turbulence models have been implemented in MS-FLUKSS, as well as a fluid dynamics pickup ion model. This allows us to compare not only bulk properties of the solar wind, but also fluctuating variables.**
4. **Comparison with in situ data at New Horizons show a good agreement for the periods of time when OMNI data indeed represent the flow in the spacecraft direction.**